

Monitoring parton equilibration in heavy ion collisions via dilepton polarization

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(Dated: February 25, 2013)

In this note we discuss how angular distribution of the dileptons produced in heavy ion collisions at RHIC/LHC energies can provide an information about a degree of local equilibration of the quark-gluon plasma produced at different invariant mass regions.

PACS numbers:

I. INTRODUCTION

The issue of parton equilibration in heavy ion collisions is an area of very active research. As it is well known, successful hydrodynamical description of the elliptic flows [1–4] implies that the beginning of (transverse) hydrodynamical expansion cannot start later than $\sim 1/2 fm/c$ after the collision moment. Perturbative mechanisms such as e.g. “bottom-up” equilibration discussed in [5] have difficulties explaining how can it happen so rapidly. On the other hand, applications of the AdS/CFT language [6–9] naturally ascribe the thermalization time to the “in-fall time” into an emerging black hole horizon, which is of the order of its position in the holographic coordinate $\sim 1/\pi T_i \sim 0.2 fm/c$.

Recent studies [8, 9] have followed a set of arbitrarily chosen initial conditions through numerical solution of the Einstein equations. At late time a convergence with a hydrodynamical description is observed, as expected. A somewhat surprising finding is that agreement with viscous hydrodynamics is reached when the anisotropy is still quite large. We would like therefore to distinguish the “*hydronization*” [12] time, at which local stress tensor $T^{\mu\nu}$ agrees with hydrodynamical one and the “*anisotropization*” time, at which all distributions become local (independent on gradients) and thus isotropic. (Both with a prescribed accuracy, of course.)

This letter is not however about theory of equilibration, but about experimental ways to monitor it in experiment. Its idea is known in general, but in this short note i would like to provide some numerical illustrations of the magnitude of the effect which can be observed in RHIC/LHC heavy ion experiments.

Let us on the onset remind standard terminology to be used below. The sources of the dileptons are split into three categories:

- (i) instantaneous parton annihilation, known as the Drell-Yan process;
- (ii) the pre-equilibrium stage, after the nuclei pass each other;
- (iii) equilibrated stage, in which matter is assumed to be local and isotropic.

II. ANGULAR ANISOTROPY

It is well known that when spin-1/2 particles (such as quarks) annihilate and produce lepton pairs, the cross section is not isotropic but has the following form

$$\frac{d\sigma}{d\Omega_k} \sim (1 + \cos^2\theta_k) \quad (2.1)$$

where the subscript correspond to a momentum k of, say, the positively charged lepton. This distribution is, for example, observed in the so called Drell-Yan pairs from stage (i), produced by the instantaneous annihilation of the quark-antiquark partons into dileptons. At high energies the partons naturally are collinear to the beams.

For illustration, let us take a particularly simple one-parameter angular distribution

$$W \sim \exp[-\alpha \cos^2\theta_p] \quad (2.2)$$

with one parameter α . The subscript p reminds us that this angle is of the colliding partons, not final leptons. Fig.1 shows two opposite examples of (normalized) distributions.

Let us now calculate the distribution of the dileptons corresponding to the distribution (2.2)

$$\begin{aligned} \frac{d\sigma}{d\Omega_k} = & \frac{1}{4\text{erf}(\sqrt{\alpha})\sqrt{\pi}\alpha} [6\text{erf}(\sqrt{\alpha})\sqrt{\pi}\alpha \\ & + 2\sqrt{\alpha}e^{-\alpha} - \text{erf}(\sqrt{\alpha})\sqrt{\pi} \\ & + \cos^2\theta_k(-6\sqrt{\alpha}e^{-\alpha} + 3\sqrt{\pi}\text{erf}(\sqrt{\alpha})) \\ & - 2\sqrt{\pi}\text{erf}(\sqrt{\alpha})\alpha] \sim 1 + a(\alpha)\cos^2\theta_k \end{aligned} \quad (2.3)$$

The last expression is a definition of the effective parameter $a(\alpha)$, which we plot in Fig.1. Note that large negative values of the α , corresponding to partons collimated near the beam direction and Drell-Yan process $a \approx 1$, as already noticed.

On the other hand, the second stage of the collision (ii) is characterized by the longitudinal pressure smaller than the transverse one. One may understand that because such anisotropic parton distribution with small differences in longitudinal momenta is produced by a “self-sorting” process, in which partons with different rapidities get spatially separated after the collision. We thus expect at this stage large negative α , in terms of the

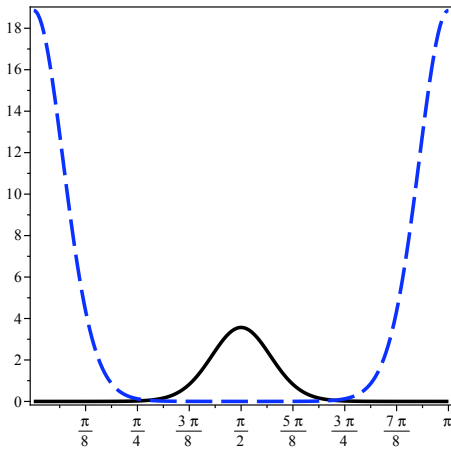


FIG. 1: (Color online) Two examples of the angular distribution in polar angle θ . The (black) solid curve corresponds to $\alpha = 10$, and the (blue) dashed one to $\alpha = -10$.

parameterization we use. One then finds that the corresponding asymptotic value of the anisotropy to be

$$a(\alpha \rightarrow \infty) = -1/3 \quad (2.4)$$

Finally, when equilibration is over, at stage (iii) the local distributions get isotropic, $\alpha \rightarrow 0$, and the anisotropy $a(0) = 0$.

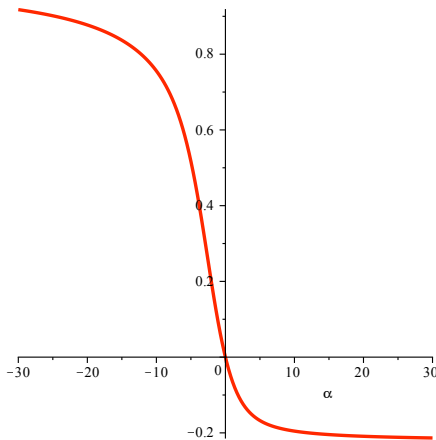


FIG. 2: (Color online) Dependence of the dilepton polarization parameter a on the parton distribution parameter α

III. DILEPTON INVARIANT MASS CAN BE USED AS A CLOCK

Qualitatively it is clear that the most massive dileptons should come from earlier stages. The quantitative relation between the invariant mass and the proper time of the production has been studied already in the first paper suggesting dileptons as a diagnostic tool for QGP [10]. It is convenient to introduce the so called “temperature profile” function

$$\begin{aligned} \frac{dN_{e^+e^-}}{dM} &= \int d^4x W(T(x)) = \int \int dT d^4x \delta(T - T(x)) W \\ &= \int dT W(T) \Phi(T) \end{aligned} \quad (3.1)$$

where $\Phi(T) = \int d^4x \delta(T - T(x))$ is the space-time volume in a fireball in which the temperature is between $T, T + dT$. Typically the production rate $W \sim \exp(-M/T)$ is exponentially decreasing at small T , while the profile, which can be approximately parameterized in a power form $\Phi(T) \sim 1/T^p$ is strongly increasing toward later times and smaller T . The product has a sharp maximum at the temperature $T^* = M/p$

$$W(T)\Phi(T) \sim \exp\left[-\frac{p^3}{2M^2}(T - T^*)^2\right] \quad (3.2)$$

Its width gets small if the power p is large, which is in fact the case, $p \sim 5-7$ or so. The smallness of this width defines the accuracy of this clock.

IV. SUMMARY AND DISCUSSION

The Drell-Yan process (i) dominates for large mass dileptons above the charmonium region $M > 4 \text{ GeV}$: here α is large and negative and the anisotropy parameter is $a \approx 1$.

The preequilibrium phase (ii) mostly produce the so called Intermediate mass dileptons (IMD), with $m_\phi < M < m_{J\psi}$. here we expect large positive α and negative anisotropy $a \approx -0.2$.

The later well-equilibrated stage (iii) produces smaller mass dileptons $M < 1 \text{ GeV}$ which tend to be unpolarized, with $\alpha \rightarrow 0, a \rightarrow 0$.

The main message of this note is directed toward experimentalists: the dependence of the anisotropy parameter on the dilepton mass $a(M)$ turns out to be of great interest and thus should be measured. As we argue, it will change from 1 to a negative value before going to zero. The most negative value measured in experiment can be compared to our Fig.2, from which one can read effective angular distribution parameter α of the quark distribution.

Finally, let us end with a message to theorists. Important simplifying assumption made above is that anisotropy of the stress tensor can be directly translated into the anisotropy of parton distribution in the plasma.

This would be true in kinetic (weak coupling) description of QGP, but unfortunately strongly coupled sQGP is much more complex, in particular it does not allow for partonic quasiparticle description at all. Furthermore, it was emphasized [6] that in out-of-equilibrium setting the average stress tensor (given by a one-point observer) contains information different from what is provided by the non-local (two-point, or spectral) observers. Basically the same message comes out from more recent study [11]. It is also not obvious that spectral information in

scalar or graviton correlators are the same as in the vector channel, relevant for dileptons. Thus the latter should be calculated.

Acknowledgments. This note is a result of a discussion which took place at the KITP program on novel numerical methods, ADS/CFT etc in January-March 2012. I am grateful to KITP for the support during my stay there.

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